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Far infrared phenomena in p-type MQW heterostructures under lateral electric field

V. N. Shastin†, V. Ya. Aleshkin†, N. Bekin†, R. Zhukavin†, B. N. Zvonkov‡, O. A. Kuznetsov‡, I. G. Malkina‡, A. Muravjov†, E. Orlova†, S. Pavlov†, A. Sitdikov† and E. A. Uskova‡

† Institute for Physics of Microstructures of RAS, N. Novgorod
‡ Physical-Technical Institute of N.Novgorod State University
shastin@ipm.sci-nnov.ru

Abstract. Experimental investigation of the far-infrared (FIR) optical properties connected with intersubband and impurity-to-2D subband states transitions of holes in MQW $In_xGa_{1-x}As/GaAs$ and $Ge/Ge_{1-x}Si_x$ heterostructures under lateral transport was performed. The mechanism of the inversion population and the far infrared amplification on the excited states to QW state transitions under lateral heating is proposed.

Introduction

The FIR pulsed p-Ge laser [1] intracavity electroabsorption method was developed and used for the investigation far-infrared transparency of heterostructures for the first time. The method allows to separate the hole and the lattice impacts in the FIR absorption. The measurements were made using the p-Ge laser radiation bands $50 \div 60$ cm^{-1} and $80 \div 125$ cm^{-1} with Faraday configuration of the magnetic fields $0.5 \div 2$ T.

The main advantage of this method is the ultrahigh sensitivity for the change of the MQW absorption coefficient. The sensitivity of relative deviation of transparency ($\Delta T/T \simeq 10^{-3}$) was determined both the pumping electric field instability and the cooling conditions. All results were interpretated in the frame of quasiclassical approach of hole heating. Energy diagrams of 2D holes (see the method [2]) and matrix elements in the case of intersubband and impurity-to-continuum states optical transitions were estimated using simplified model [3].

1 $In_xGa_{1-x}As/GaAs$ MQW heterostructures with δ-doped barriers

δ-doped p-type $In_xGa_{1-x}As/GaAs$ MQW heterostructures were grown by MOCVD technique on GaAs(001) substrates and contain 20 periods with $In_xGa_{1-x}As$ quantum wells ($0.08 \le x \le 0.19$), layer thickness $d = 46 \div 152$ Å, separated by GaAs 600 Å barriers. Carbon δ-layers with the doping level $N_A = 10^{11} \div 3 \times 10^{12}$ cm^{-2} were introduced in GaAs barrier with the distance L from the quantum well edge changing from 25 to 136 Å. 20 period heterostructures were grown by MOCVD technique on GaAs(001) substrates with $In_xGa_{1-x}As$ quantum wells ($0.08 \le x \le 0.19$), layer thickness $d = 46 \div 152$ Å, separated by GaAs 600 Å barriers. Carbon δ-layers with the doping level $N_A = 10^{11} \div 3 \times 10^{12}$ cm^{-2} were introduced in GaAs closed to QW barrier interface on the distance L changed from 25 to 136 Å (see Table 1.).

Table 1. $In_xGa_{1-x}As/GaAs{:}C$ MQW heterostructures.

No. #	spacer L (Å)	qw d (Å)	x	N_A (cm^{-2})
1797	53	79	0.19	3.4×10^{11}
1799	47	71	0.2	5.7×10^{10}
1801	50	49	0.18	2×10^{11}
1850	48	48	0.1	1.8×10^{11}
1884	—	0	—	2.6×10^{11}
1942	51	50	0.086	2.2×10^{11}
1943	90	46	0.107	2.2×10^{11}
1944	136	46	0.11	2.65×10^{11}
1945	25	50	0.107	2.5×10^{11}
1946	48	152	0.137	3.1×10^{11}
1947	51	52	0.11	3.1×10^{11}
2018	50	50	0.1	1.5×10^{12}
2019	50	50	0.1	2×10^{12}
2022	50	50	0.1	7.1×10^{11}

1.1 Far-infrared hole amplification in heterostructures with shallow quantum wells

The resonant increase of the FIR transparency under the electric field was observed for heterostructures #1947, #1943 with narrow QW $\Delta \geq \hbar\omega$, where Δ is the gap between nearest subband and $\hbar\omega$ is FIR radiation quantum, while $E_{h,h1} \simeq E_{g.s.}$ and 50 Å $\leq L \leq$ 90 Å.

It can be explained by the amplification on the acceptor excited state to QW state transitions. The inversion population responsible for the gain is formed on the excited states due to real space transfer under the QW hole heating in strong electric fields $600 \leq E \leq 1400$ V/cm.

The mobilities of holes in the barrier ($\mu_B = 300$ cm^2/V s) and quantum well ($\mu_W =$ 3000 cm^2/V sec) regions [3] determine the difference of the effective temperatures in the quantum well $T_W \geq 400$ K and the barrier $T_B \simeq 100$ K for $E \simeq 10^3$ V/cm and $\nu_{ac} \simeq 3\times10^9$ s^{-1}. The population on the excited states is controlled by barrier temperature, if their coupling with QW states is weak. As a result the overpopulation of the excited state is reached ($f_{ex}/f_w \simeq 2$) and the expected FIR gain is 10 cm^{-1}. For the electrical field $E > 1500$ V/cm the overheating of holes in the barrier leads to the depletion of the excited states and decreases the gain.

1.2 Far-infrared hole absorption in heterostructures with shallow quantum wells

Three mechanisms can be responsible for the FIR absorption in heterostructures. The first is due to the acceptor states to the QW states optical transitions. It has place despite of the spatial separation because of the overlap of working state wavefunctions. The estimation of the absorption cross-section for $gr.st. \to$ QW$st.$ optical transitions yields $\sigma_{g.s.} \simeq 2\times10^{-16}$ cm^{-2} (effective barrier thickness $L^* \simeq 25 \div 30$ Å).

The increase of FIR transparency was observed for the heterostructures with "shallow" QW when the lowest QW subband is above the ground state ($E_{g.s.} \simeq 26$ meV)

of the acceptor $E_{h,h1} \leq E_{g.s.}$ and $L \leq 100$ Å.

Acceptor ground state to QW state transitions determine the dependence $I(E)$ on samples #1850, #1942, #1945, #2019, #2022, where typical threshold increase of the transparency is explained by acceptor breakdown.

1.3 Far-infrared intersubband hole absorption in heterostructures with deep quantum wells

The second type of FIR absorption is on the QW intersubband optical transitions, that dominates when $\Delta \simeq \hbar\omega$. At this case the electromodulation is determined by the QW holes dispersion $\mathrm{E}(k_{\|})$.

For "deep" QW $(E_{h,h1} > E_{g.s.})$ transparency was decreased under the electric field. Intersubband transitions dominate in sample #1946, where sign of the modulation corresponds to calculated subbands dispersion.

1.4 Far-infrared lattice absorption in QW and GaAs δ-doped barriers

The last FIR absorption observed is caused by the lattice absorption. The decrease of FIR transparency was observed for the heterostructures with "shallow" QW with remote $L \geq 100$ Åcarbon δ-layers (sample #1944) and also in test δ-layers structure without $In_xGa_{1-x}As$ QW layers (#1884).

The same effect on $I(E)$ decrease was observed for the heterostructures with "deep narrow" QW (sample #1801), where $\Delta \geq \hbar\omega$. Multiphonon lattice absorption is relatively weak $\alpha < 3 \times 10^{-3}$ cm^{-1}, nevertheless the method allows to register it.

2 The selectively doped p-type $Ge/Ge_{1-x}Si_x$:B MQW heterostructures

The selectively doped p-type $Ge/Ge_{1-x}Si_x$:B MQW heterostructures were grown by MOCVD technique on pure Ge(111) substrates and contain N periods D ($N = 36-300$) with Ge quantum wells, separated by $Ge_{1-x}Si_x$ barriers (Table 2.).

2.1 Far-infrared intersubband hole absorption in the heterostructure film

The modulation of FIR transparency was observed for the heterostructures with $\Delta \simeq \hbar\omega$ condition.

It has been shown that far-infrared characteristics of $Ge/Ge_{1-x}Si_x$:B heterostructures with QW width $d \approx 100$ Å for $0.07 \leq x \leq 0.1$ are determined by the optical transitions between 2D hole subbands $E_{hh1} \rightarrow E_{hh2}$ and for one with QW width $d \approx 170$ Å— by the transitions $E_{hh1} \rightarrow E_{hh3}$.

Electrical field applied along the MQW layer causes the far-infrared absorption due to redistribution of holes on nonparabolic 2D subbands. The electromodulation effect is far-infrared radiation frequency dependent that can be explained by hole energy diagram calculated [2].

2.2 Far-infrared absorption in Ge substrate

To differ the FIR optical absorption in heterostructure film and in the substrate (pure Ge with residue impurity concentration not more than 10^{13} cm^{-3}) the test experiments were performed with the sample #432a$_8$. After the growing the MQW film was etched from the substrate and both the sign and the magnitude of modulation had changed. Small effect of FIR transparency decreasing on such Ge substrate under the applied

Table 2. $Ge/Ge_{1-x}Si_x$:B MQW heterostructures.

No. #	period D (Å)	qw d (Å)	N	x	N_A (cm^{-2})
125a$_{18}$	370	175	36	0.08	$2.\times10^{11}$
360b$_3$	350	<102	92	0.06	$2.\times10^{11}$
363a$_3$	335	<105	300	0.06	1.2×10^{12}
381a$_{12}$	245	115	54	0.12	$5.\times10^{11}$
381b$_5$	270	110	54	0.12	$5.\times10^{11}$
431a$_1$	375	130	36	0.052	$2.\times10^{11}$
432a$_8$	335	135	36	0.06	$5.\times10^{11}$
444a$_1$	240	107	120	0.07	$1.\times10^{11}$
444a$_2$	270	110	120	0.067	$<10^{11}$

electric fields was registered. That was above the breakdown of Cu impurity centers ($\geq$ 600 V/cm) and caused by the lattice absorption.

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